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Effects of substituent position on aminobenzoate relaxation pathways in solution†

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The negative effects of ultraviolet radiation (UVR) on human skin have led to the widespread use of sunscreens, *i.e.* skincare products containing UV filters to absorb, reflect or otherwise block UVR. The mechanisms by which UV filters dissipate energy following photoexcitation, *i.e.* their photodynamics, can crucially determine a molecule's performance as a sunscreen UV filter. In this work, we evaluate the effects of substituent position on the in-solution relaxation pathways of two derivatives of methyl anthranilate (an *ortho* compound that is a precursor to the UV filter meradimate), *meta*- and *para*-methyl anthranilate, *m*-MA and *p*-MA, respectively. The photodynamics of *m*-MA were found to be sensitive to solvent polarity: its emission spectra show larger Stokes shifts with increasing polarity, and both the fluorescence quantum yield and lifetimes for *m*-MA increase in polar solvents. While the Stokes shifts for *p*-MA are much milder and more independent of solvent environment than those of *m*-MA, we find its fluorescence quantum yields to be sensitive not only to solvent polarity but to the hydrogen bonding character of the solvent. In both cases (*m*- and *p*-MA) we have found common computational methods to be insufficient to appropriately model the observed spectroscopic data, likely due to an inability to account for explicit solvent interactions, a known challenge in computational chemistry. Therefore, apart from providing insight into the photodynamics of anthranilate derivatives, the work presented here also provides a case study that may be of use to theoretical chemists looking to improve and develop explicit solvent computational methods.

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Introduction

The ultraviolet (UV) radiation that reaches the Earth's surface, mostly UVB (280–315 nm) and UVA (315–400 nm),¹ plays an important role in life sustaining processes such as photosynthesis in plants² or the production of vitamin D in human skin.^{2,3} Nevertheless, UV radiation may also have destructive effects on living organisms. UVB radiation, being more energetic, can cause more direct damage by being absorbed directly by DNA and thus causing mutagenic photolesions which may lead to skin cancer.^{4,5} UVA is commonly associated with skin pigmentation and skin aging, but it is also the source of oxidative stress, which may equally cause DNA mutations and lead to skin cancer.^{6,7} Moreover, the higher abundance of UVA radiation at the Earth's surface, in addition to its ability to penetrate deeper into the

skin, constitute further risks which justify the need for photoprotection against UVA as well as UVB.⁶

While human skin is naturally equipped with its own forms of photoprotection, in the form of melanin, a pigment which absorbs harmful radiation before it reaches vulnerable skin cells, this protection is a delayed response that is often insufficient against overexposure to solar radiation.^{8,9} In order to complement the skin's natural forms of photoprotection, the use of sunscreens – commercial formulations containing chemical UV filters, physical UV blockers or, often, both – is now common practice. The chemical UV filters contained in commercial sunscreen formulations are required to be non-toxic to humans and the environment while allowing for the production of a pleasant formulation. In addition, an ideal UV filter should dissipate excess energy efficiently, without undergoing or inducing any potentially harmful photochemistry. From a photophysical perspective, this translates to short-lived excited states, with excited state population returning to the electronic ground state (S_0) within a picosecond (10^{-12} second) lifetime or less, typically *via* internal conversion (IC).^{10–12} Fast excited state relaxation ensures not only that the UV filter is less vulnerable to harmful photochemistry but

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also that it is quickly 'recycled' and thus able to re-absorb UV radiation. In turn, this 'recycling' of the UV filter ensures the commercial sunscreen formulation maintains its photoprotective performance for longer periods of time.

The anthranilates constitute one of the families of chemical UV filters currently employed in commercial sunscreen formulations.¹³ Anthranilates are molecules for which the *ortho* positioning of an amine and an ester functional group facilitates an intramolecular hydrogen bond between them. Menthyl anthranilate, or meradimate, a UV filter currently approved by the Food and Drug Administration of the United States of America for use in commercial sunscreen formulations,¹³ has previously been studied in order to establish its photophysics and hence the mechanisms by which it dissipates excess energy. In one such study, which combined experimental and computational insight, it has been found that absorption of UVA/UVB radiation leads both meradimate and its precursor methyl anthranilate (an *ortho* compound, *o*-MA) to undergo an incomplete excited state intramolecular proton transfer, for which the hydrogen atom is dislocated along the N–H–O hydrogen bond,¹⁴ being unable to then access any nearby conical intersections (CIs) that would allow IC to take place. As a result, the excited state population is trapped in the S_1 state and relaxation happens mostly *via* radiative pathways, *i.e.* fluorescence and phosphorescence.¹⁴ This scenario is non-ideal for a sunscreen molecule, not only due to the formation of often undesirable triplet states but also because excess energy persists for longer periods of time, making the molecules more vulnerable to reactive relaxation pathways.^{10–12}

In previous work carried out in the gas-phase, it has been shown that changing the substituent position (and thus disturbing the intramolecular hydrogen bond) of the anthranilates has a significant impact on both the resulting absorption spectra and the observed photodynamics.¹⁵ Specifically, it has been suggested that, in the gas-phase, the relaxation pathway of methyl-3-aminobenzoate, (*m*-MA, see Fig. 1 for molecular structure) may involve prefulvenic CIs, that is, ring distortions which push one of the carbon atoms in the six membered ring away from the ring plane.¹⁵ On the other hand, the long gas-phase lifetime (>1.2 ns) of the excited state of methyl-4-aminobenzoate (*p*-MA, see Fig. 1) was suggested to be due to the

stability afforded by the charge transfer characteristic of this state.¹⁵ Moreover, it was established that while both *m*-MA and *p*-MA fluoresce in solution, luminescence is non-unity ($<100\%$) and hence alternative, non-radiative pathways must be involved in the photodynamics of these molecules.¹⁵

In the present work, we investigate the effects of substituent position on the ultrafast photodynamics of these aminobenzoates, *m*-MA and *p*-MA, in solution, having pursued both experimental work and computational modelling. We evaluate also the effects of environment polarity and protic characteristics on the photodynamics of these molecules. In a sunscreen context, the ultrafast photodynamics of solvated *p*-MA are particularly interesting, since *p*-MA is the ester derivative of *para*-aminobenzoic acid (PABA), a once widely used UV filter that lost its place in commercial sunscreen formulations due to photosensitivity and photoallergy concerns.^{16,17}

Experimental methods

i. Steady-state spectroscopy

The UV/Vis absorption spectra of *m*-MA (methyl-3-aminobenzoate, Alfa Aesar, $\geq 98\%$) and *p*-MA (methyl-4-aminobenzoate, Aldrich, 98%) were obtained using an Agilent Cary 60 UV/Vis spectrophotometer for separate solutions of each molecule dissolved in cyclohexane (CHX, Merck, $\geq 99.7\%$), acetonitrile (ACN, Fisher Scientific, $\geq 99.8\%$), and ethanol (EtOH, VWR, absolute) to a concentration of approximately 10^{-6} M. Temperature-dependent UV/Vis absorption spectra were also obtained for equivalent solutions using an Agilent Cary 60 UV/Vis spectrophotometer equipped with a temperature control unit (TC 1 Temperature Controller, Quantum NorthWest); these spectra can be found in the ESI† Section 1 (S1).

The emission spectra for both *m*-MA and *p*-MA were obtained for each solution with a Horiba Scientific Fluorolog[®]-3. The same instrument was used to determine fluorescence quantum yields for these solutions, as presented in the ESI† in Section 2 (S2). Fluorescence lifetimes were also determined, albeit employing different equipment: for *m*-MA, the fluorescence lifetimes were obtained with the Horiba Scientific Fluorolog[®]-3, while for *p*-MA these were measured using a Time-Correlated Single Photon Counting (TCSPC) technique. Further details on the procedures followed for these measurements are given in Section 3 of the ESI† (S3).

ii. Transient electronic absorption spectroscopy (TEAS)

The transient electronic absorption spectroscopy (TEAS) set-up used in the present experiments has been described previously in greater detail^{18–20} and it will therefore be only briefly summarised here, with specific details pertaining to the present work being provided. TEAS measurements were obtained for separate solutions of *m*-MA and *p*-MA dissolved in CHX, ACN and EtOH to a concentration of 10^{-3} M. To ensure that fresh sample is interrogated with each laser pulse, the sample solutions were recirculated through a flow cell (Harrick Scientific), consisting of two CaF₂ windows separated by 100 μm

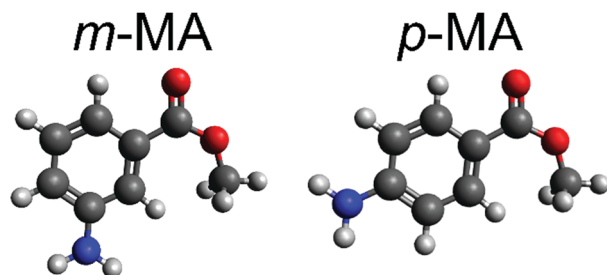


Fig. 1 Molecular structures of (left) *meta*-methyl anthranilate (*m*-MA, methyl-3-aminobenzoate) and (right) *para*-methyl anthranilate (*p*-MA, methyl-4-aminobenzoate). White, grey, red and blue spheres correspond to hydrogen, carbon, oxygen and nitrogen atoms, respectively.



thick PTFE spacers (500 μm for *m*-MA, for improved signal), using a SIMDOS 02 diaphragm pump (KNF Neuberger UK Ltd).

The fundamental 800 nm output (12 W, 1 kHz) of a commercial femtosecond (fs) Ti:Sapphire regenerative amplified laser system (Spectra-Physics, Dual Ascend Pumped Spitfire Ace) seeded by a Mai Tai (Spectra-Physics), was split into four fractions of approximately equal power (3.5 W), each one having a separate recompression grating. A 2.5 W fraction of one of these beams was seeded into an optical parametric amplifier (Topas-Prime with UV extension, Light Conversion) to generate the pump pulses used in the reported TEAS experiments. The pump wavelength (λ_{pu}) was centred at the absorption maxima (λ_{max}) for each solution. Moreover, the power of the pump pulse was set to 0.4–0.6 mW, and power dependence studies were carried out in order to ensure single-photon dynamics at these powers; see Section 4 of the ESI† for more details (S4). The probe pulses (λ_{pr}), on the other hand, were generated by focusing 5% of the remaining 1 W of the 800 nm fundamental beam into a CaF_2 window (2 mm thick, vertically translated to avoid damage), thus creating the broadband white light continuum (320–720 nm); the 800 nm beam was further attenuated with a variable neutral density filter as required to produce stable white light. The relative polarisation between the pump and probe beams was held at magic angle (54.7°) by means of a $\lambda/2$ waveplate in order to negate any rotational dynamics.

At the sample-laser interaction point, λ_{pu} photoexcites the species of interest and λ_{pr} probes the resulting excited state at predetermined pump–probe time interval delays (Δt), thus allowing for excited state dynamics to be monitored. Pump–probe delays ranging from -1 ps to 3 ns (where $\Delta t = 0$ corresponds to the pump and probe pulses arriving at the sample at the same time) are achieved by translating a hollow gold retroreflector on a motorized optical delay line (Newport M-IMS500CCHA) in the λ_{pr} beam path. Between -1 and 1 ps, the Δt step size is fixed, and after that it is increased as described by Megerle *et al.*,²¹ this is to ensure an optimum balance between detailed mapping of the dynamics and reasonable acquisition times. The portion of the probe beam transmitted through the sample was collected using a fibre-coupled spectrometer (Avantes, AvaSpec-ULS1650F). Changes in optical density (ΔOD) were calculated from the measured probe intensities transmitted through the sequentially excited and non-excited sample as prepared by employing a mechanical chopper in the pump beam path.

The transient absorption spectra (TAS) collected as just described are chirped, *i.e.* $\Delta t = 0$ is different for each λ_{pr} , due to group velocity dispersion (GVD) artefacts;²² this chirp was corrected in the data herein presented using the KOALA package.²³ When extracting quantitative dynamical information from the TAS with a global fitting procedure within the Glotaran software package,²⁴ a third order polynomial is included in the algorithm to account for this chirp effect. The algorithm within Glotaran also convolves the Gaussian instrument response function (IRF) with exponential functions following a sequential kinetic model (*i.e.* assuming

$A \xrightarrow{\tau_1} B \xrightarrow{\tau_2} C$) to extract time constants (τ_n) and their associated evolution associated difference spectra (EADS) for each data set collected, as further detailed in S5 of the ESI.† The setup used in these experiments provides an IRF with a full width at half maximum of ~ 70 –140 fs (depending on solvent, λ_{pu} and λ_{pr} , see S6 of the ESI†). The quality of the fits was evaluated upon inspection of the resulting residuals and fit lineouts, also shown in the ESI,† in S7.

Finally, ‘long-time’ transient absorption spectra ($\Delta t = 0$ –100 ns, LT-TAS) were also obtained for *p*-MA. For these LT-TAS measurements, solutions of *p*-MA were prepared in CHX, ACN, and EtOH, adjusting the concentration to an optical density between 0.3 and 0.5 OD at 266 nm. The solutions were placed in quartz cuvettes and studied without further preparation. LT-TAS measurements were then performed for these solutions in an LP980-KS spectrometer (Edinburgh Instruments Ltd) configured with a visible PMT detector for kinetic data and an ICCD detector for spectral data acquisition. These detectors were mounted on different ports of the LP980 spectrograph, allowing rapid switching between spectral and kinetic detection. Pump pulses at 266 nm were produced by a Litron Nano S 130-10 laser (Litron Lasers Ltd). The pump pulse width was ~ 5 ns and its energy was ~ 8 mJ pulse⁻¹. The white light probe beam was generated by the Xe lamp in the LP980 spectrograph, operating in pulsed mode and producing pulses with a duration of 6 ms. Pump-only and probe-only backgrounds were subtracted automatically by the L900 software when necessary. Spectral and kinetic ΔOD curves were calculated automatically by L900.

Computational methods

All calculations were conducted using the NWChem software package.²⁵ Initially, the geometries of *m*-MA and *p*-MA were optimised at the PBE0/cc-pVTZ level of theory.²⁶ *m*-MA can relax into two possible forms, one with the methyl group pointing towards the amine group and one with it pointing away. Both *m*-MA structures were investigated but gave very similar results; as such, hereafter we restrict discussion to the structure with the methyl group pointing away from the amine group, as this structure had a slightly lower ground state energy. Following geometry optimisation, both *m*-MA and *p*-MA were reoptimized using an implicit solvent model^{27,28} for each of the three solvents, CHX, ACN, and EtOH, using default parameters from the Minnesota Solvent Descriptor Database.²⁹ Vertical excitation calculations were then conducted for each of these structures with each choice of implicit solvent, using the same level of theory as before, in both the singlet and triplet manifold.

Reaction coordinates were probed in implicit-solvent ethanol along the static rotation coordinate of both the amino and ester groups of *m*-MA and *p*-MA (see Fig. 6 and ESI†) through equidistant steps along the coordinate. Vertical excitations were calculated at each step, again using the PBE0/cc-pVTZ level of theory. This process was repeated for rotations of the amino and ester groups of both *m*-MA and *p*-MA, as well as the



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explained by a strong, broad excited state absorption feature which is overlapped by a negative stimulated emission feature. The stimulated emission feature would correspond to the dip in signal observed at approximately 350–400 nm (depending on solvent), which also broadly matches the *m*-MA emission in each solvent, as presented Fig. 2.

The hypothesis of a single excited state absorption feature overlapped by a stimulated emission feature appropriately accounts for the evolution of EADS1 into EADS2 for *m*-MA in CHX (see Fig. 4(d)). Within $\tau_1 = 1690 \pm 160$ ps, the dip at ~ 360 nm disappears, leaving behind a single, broad excited state absorption feature which remains for $\tau_2 > 3$ ns. Assuming the dip at ~ 360 nm does indeed correspond to a stimulated emission feature, this would imply that τ_1 in this case corresponds to the fluorescence lifetime. In fact, the value of τ_1 extracted from these experiments is in remarkable agreement with the previously reported fluorescence lifetime of *m*-MA in CHX of $\tau_{\text{Fl}} \sim 1.7$ ns,¹⁵ which supports our assignment of τ_1 to the fluorescence lifetime of *m*-MA in CHX.

The relatively fast fluorescence observed for *m*-MA in CHX, along with the small Stokes shift observed in this case (37 nm, Fig. 2), suggests that emission takes place from the close vicinity of the Franck–Condon region. However, as evidenced by the TAS in Fig. 4, some of the excited state population remains in the S_1 state of *m*-MA beyond the temporal window of the present experiments ($\Delta t = 3$ ns), suggesting the existence of a nearby energy minimum where excited state population can be trapped. The non-unity quantum yield of fluorescence previously reported for *m*-MA in CHX ($\Phi_{\text{Fl}} = 0.25$),¹⁵ implies that alternative relaxation pathways play a significant role in excited state relaxation in this case, which could also be acting as efficient sinks for excited state population and thus contributing to the observed fast fluorescence lifetimes. These alternative pathways could include intersystem crossing (ISC) onto the triplet manifold and subsequent phosphorescence, or internal conversion (IC) onto the ground state, even though we have no direct evidence of either relaxation pathway. While we have been unable to computationally identify a conical intersection (CI) between the S_1 and S_0 states of *m*-MA in implicit solvent, we have previously reported on several prefulvenic (ring distortion) CIs that may be accessible to MA, thus facilitating IC.¹⁵

Despite the significant differences in the emission spectra, the transient absorption spectra (TAS) obtained for *m*-MA are similar across the solvents studied, as can be seen in Fig. 4. In all solvents, the TAS seem to be predominantly described by two excited state absorption features which are present immediately after photoexcitation at the λ_{\max} for each solution. However, given that photoexcitation of *m*-MA is likely to result in exclusive population of the S_1 state (see Table 1 and discussion above), the appearance of the TAS in Fig. 4 is best

	CHX			ACN			EtOH		
State	eV	Character	Oscillator strength	eV	Character	Oscillator strength	eV	Character	Oscillator strength
	<i>m</i> -MA								
S ₂	4.97	nπ*	0.0002	5.01	nπ*	0.0002	5.12	nπ*	0.0003
S ₁	4.03	ππ*	0.0532	3.94	ππ*	0.0529	3.87	ππ*	0.0524
T ₂	3.50	ππ*	—	3.49	ππ*	—	3.48	ππ*	—
T ₁	3.06	ππ*	—	3.00	ππ*	—	2.94	ππ*	—
	<i>p</i> -MA								
S ₂	4.78	ππ*	0.3345	4.71	ππ*	0.0283	4.71	ππ*	0.0180
S ₁	4.77	ππ*	0.1489	4.66	ππ*	0.4830	4.60	ππ*	0.5048
T ₂	4.01	ππ*	—	3.92	ππ*	—	3.94	ππ*	—
T ₁	3.20	ππ*	—	3.14	ππ*	—	3.10	ππ*	—

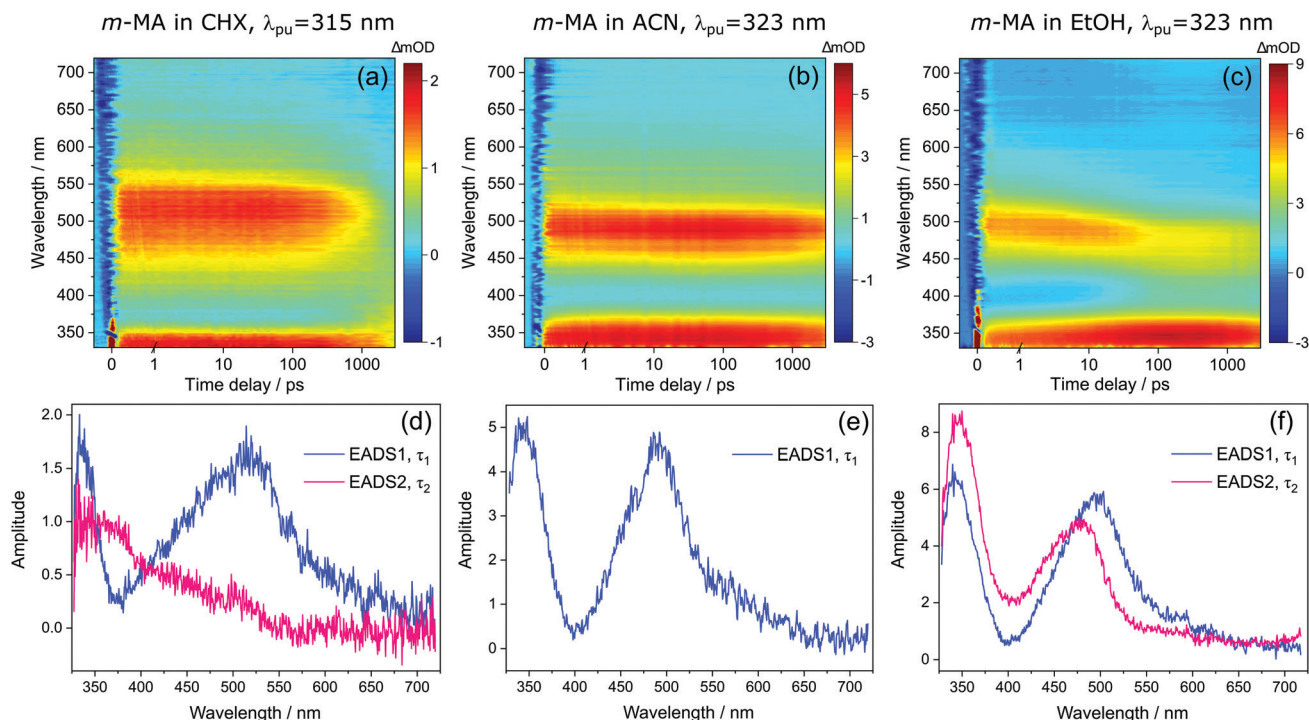


Fig. 4 Transient absorption spectra (TAS) collected for *m*-MA in (a) CHX, (b) ACN and (c) EtOH after photoexcitation at their respective λ_{pu} (315 nm, 323 nm and 323 nm, respectively), shown as false colour heat maps. Time delay axis is shown as a linear scale until 1 picosecond and as a logarithmic scale thereafter. Also shown are the corresponding evolution associated difference spectra (EADS) extracted from globally fitting the data with the Glotaran software package, for *m*-MA in (d) CHX, (e) ACN and (f) EtOH.

Table 2 Summary of the time constants extracted with a global fitting technique (assuming a sequential kinetic model) from the TAS collected for solutions of *m*-MA and *p*-MA dissolved in CHX, EtOH, and ACN, following photoexcitation at λ_{pu} . All errors quoted are those associated with the corresponding fits

<i>m</i> -MA						
Solvent	τ_1/ps	τ_2/ns	$\tau_{\text{FI}}^a/\text{ns}$	Φ_{FI}	Stokes shift (nm/cm ⁻¹)	
CHX	1690 ± 160	> 3	1.7 ¹⁵	0.25 ¹⁵	37/3317	
ACN	> 3000	—	10.24 ± 0.02	0.78 ± 0.02	77/5960	
EtOH	22.4 ± 0.9	> 3	14.00 ± 0.03	0.64 ± 0.02	102/7431	
<i>p</i> -MA						
Solvent	τ_1/ps	τ_2/ps	τ_3/ps	$\tau_{\text{FI}}^a/\text{ns}$	Φ_{FI}	Stokes shift (nm cm ⁻¹)
CHX	3.84 ± 0.05	460 ± 10	> 3	1.949 ± 0.003	0.08 ¹⁵	37/4433
ACN	1.35 ± 0.02	526 ± 6	> 3	1.029 ± 0.002	0.45 ± 0.001	37/4005
EtOH	12.8 ± 0.1	135 ± 1	> 3	0.390 ± 0.001	0.15 ± 0.07	41/4162

^a The values of τ_{FI} for *m*-MA were determined using the Horiba Scientific Fluorolog[®]-3, while those of *p*-MA were determined by TCSPC (see ESI† for further details). Superscript numbers denote the reference from which the value was taken.

The photodynamics of *m*-MA were also studied in two polar solvents, a polar aprotic solvent, ACN, and a polar protic solvent, EtOH, in order to evaluate any potential effects of the hydrogen bonding. In both ACN and EtOH, the TAS of *m*-MA are slightly different to that observed in CHX. Taking forward the assumption that the dip in signal, which in ACN is centred at ~400 nm (see Fig. 4(e)), corresponds to a stimulated emission feature overlapping a broader excited state absorption feature, we can conclude that photoexcitation of the *S*₁ state of *m*-MA in ACN results in trapped excited state population:

both the excited state absorption and the stimulated emission feature are immediately present in the TAS and remain for $\tau_1 > 3$ ns. This is consistent with the fluorescence lifetime measured for *m*-MA in ACN, $\tau_{\text{FI}} = 10.24 \pm 0.02$ ns (see ESI†), corroborating the long-lived *S*₁ state and respective fluorescence observed in the TAS. The trapping of excited state population in *S*₁, as evidenced by both the TAS and the fluorescence lifetime measurements of *m*-MA in ACN, is also consistent with the existence of a relatively deep energy minimum along the *S*₁ state which, as discussed above, we could not



In summary, we hypothesise that the ultrafast photodynamics of *m*-MA in solution are determined by the solvent-dependent

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what is observed when the NH_2 group is replaced by a $\text{N}(\text{CH}_3)_2$ group, as reported and reviewed by Lippert *et al.*³⁸ While the lack of double fluorescence in *p*-MA had already been reported by Aleksiejew *et al.*,⁴⁰ the reasoning for this marked difference remained elusive.

In order to elucidate the reasons for a lack of double fluorescence in *p*-MA when compared to its methylated amine form, we have produced PECs along the rotation of both the NH_2 and the $\text{N}(\text{CH}_3)_2$ groups with respect to the benzene ring, as shown in Fig. 6. This rotational motion would correspond to the 'twist' undergone by TICT systems. It is clear that the S_1 state of the methylated *p*-MA has a marked energy minimum at the point in $\text{N}(\text{CH}_3)_2$ rotation where the methyl units are positioned on the plane perpendicular to that of the ring (90° dihedral angle). On the S_2 state, on the other hand, there is a barrier along the TICT coordinate which traps excited state population in the locally excited minimum, from which fluorescence can also take place.³⁸ The relative positions of the S_1 and S_2 states and barriers is affected by solvent polarity and ultimately defines the observed fluorescence spectra, including the double fluorescence observed by Lippert *et al.*³⁸

When the equivalent rotation is evaluated for the NH_2 group in *p*-MA, no TICT energy minimum is evident: the S_1 excited state is virtually isoenergetic across the rotation coordinate (from 0° to 180°) and hence there is no driving force for a 'twist' to take place as it would for a TICT system. The lack of pronounced Stokes shifts in *p*-MA, regardless of solvent polarity as shown in Fig. 5, is also indicative of no large geometry changes taking place in the excited state. Given the small Stokes shifts observed for *p*-MA in any of the three solvents studied (see Table 2 for Stokes shift values), it is plausible to assume that the implicit ethanol PECs in Fig. 6 would be unaffected by solvent. Finally, it is worth noting that the lack of double fluorescence observed for *p*-MA is also consistent with the behaviour of its acid form, *para*-aminobenzoic acid (PABA), which was one of the earliest patented sunscreens and was very commonly used prior to its prohibition in cosmetic use in the European Union.^{41,42} Similar to what we report here

for *p*-MA, PABA was also found to have single peak fluorescence, revealing a lack of photoexcited TICT.⁴¹

Bearing in mind the above observations, we now move to present and discuss the TAS obtained for *p*-MA in the different solvents studied, shown in Fig. 7. We consider first the excited states accessed upon photoexcitation of *p*-MA at its absorption maxima in each solvent. The first and second excited electronic states of *p*-MA (S_1 and S_2 , respectively) are nearly isoenergetic in CHX, with an energy difference between them of just 80 cm^{-1} , as revealed by our vertical excitation energy calculations (Table 1). The close energies of these S_1 and S_2 states are also evidenced by the absorption spectrum of *p*-MA in CHX (shown in Fig. 5), which shows a main peak centred at 271 nm (S_2), with a discernible shoulder at 281 nm (S_1). These observations are in line with those reported by Aleksiejew *et al.*⁴⁰ Despite the larger energy differences between the S_1 and S_2 states of *p*-MA in ACN and EtOH (404 cm^{-1} and 888 cm^{-1} , respectively), the bandwidth of $\sim 500\text{ cm}^{-1}$ of the laser pulses used in the present TEAS experiments is likely to result in simultaneous photoexcitation of both the S_1 and S_2 states in *p*-MA, albeit to a lesser extent in EtOH. In addition, in CHX the oscillator strength of the S_2 state of *p*-MA has been calculated to be larger than that of the S_1 , as shown in Table 1. In ACN and EtOH, the calculated oscillator strength of the S_2 state is significantly smaller than that of the respective S_1 states (see Table 1). Nevertheless, given the small S_1 – S_2 energy gaps determined by our calculations for *p*-MA, the discussion hereon assumes that both the S_1 and S_2 states of *p*-MA can be populated, to some extent, upon photoexcitation at $\lambda_{\text{pu}} = 271\text{ nm}$, 285 nm and 294 nm in CHX, ACN, and EtOH, respectively.

Despite significant differences in the time constants obtained from the TAS for *p*-MA shown (see Table 2), the observed spectral features can be explained by the same combination of photophysical processes in all three solvents. When photoexciting *p*-MA in either EtOH or ACN at their respective absorption maxima ($\lambda_{\text{pu}} = 294\text{ nm}$ and 285 nm , respectively), a strong stimulated emission feature is observed at approximately 340 nm . This stimulated emission feature sensibly

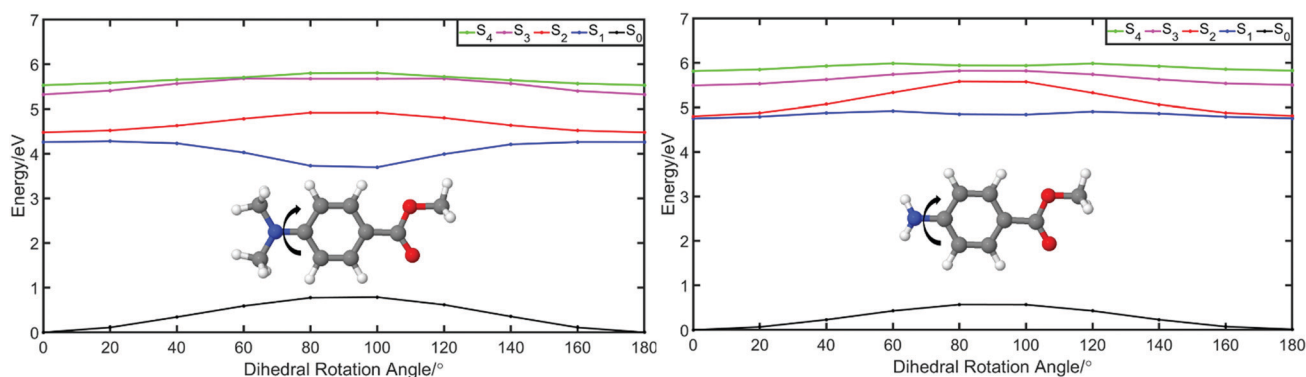


Fig. 6 A plot of the calculated energies of the ground (S_0 , black) and first four excited states of methylated *p*-MA (left) and *p*-MA (right): S_1 (blue), S_2 (red), S_3 (pink), and S_4 (green). The arrows illustrate the dihedral angle that has been rotated in order to probe for local minima: in *p*-MA, the NH_2 group is rotated, while in its methylated form it is the $\text{N}(\text{CH}_3)_2$ group that rotates. The origin, at 0 degrees, denotes the Franck–Condon region, with each subsequent angle being the rotation along the respective dihedral angle. These potential energy curves were produced at the PBE0/cc-pVTZ level of theory, and all calculations were conducted using implicitly modelled ethanol.



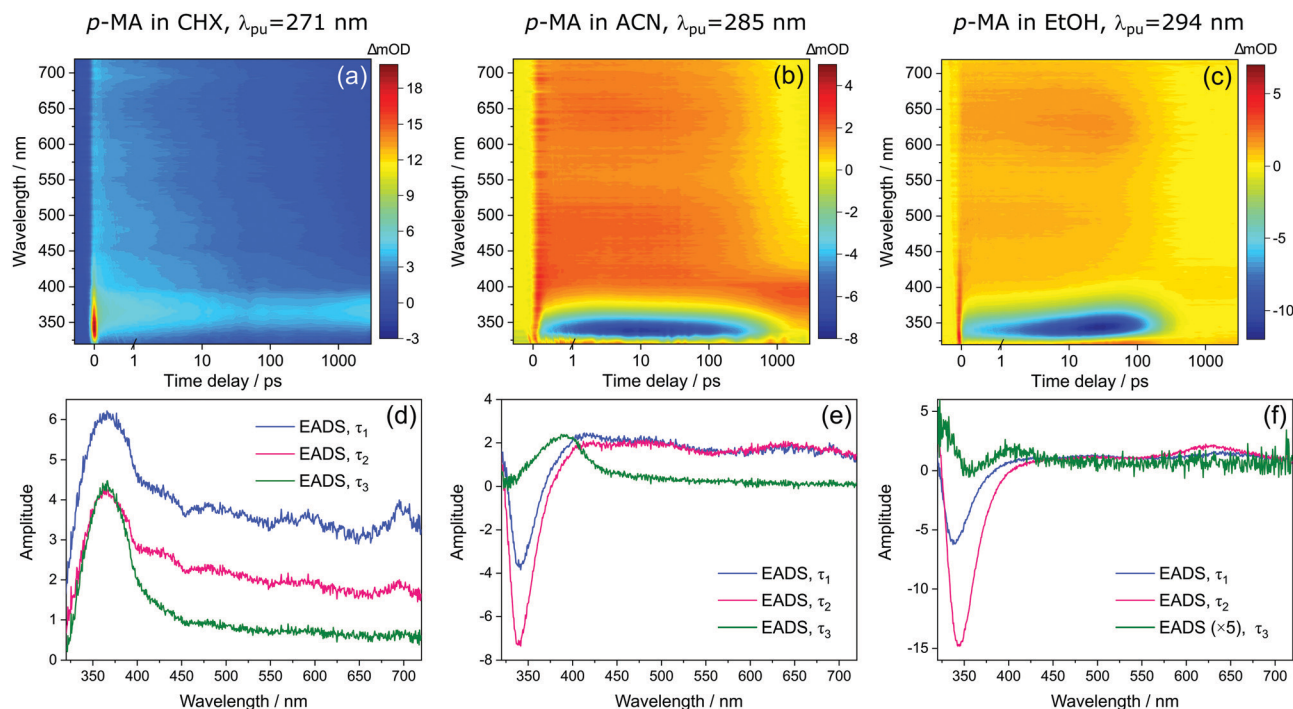


Fig. 7 Transient absorption spectra (TAS) collected for *p*-MA in (a) CHX, (b) ACN and (c) EtOH after photoexcitation at their respective λ_{pu} (271 nm, 285 nm and 294 nm, respectively), shown as false colour heat maps. Time delay axis is shown as a linear scale until 1 picosecond and as a logarithmic scale thereafter. Also shown are the corresponding evolution associated difference spectra (EADS) extracted from globally fitting the data with the Glotaran software package, for *p*-MA in (d) CHX, (e) ACN and (f) EtOH.

matches with the fluorescence of *p*-MA reported in Fig. 5; its absence in the TAS for CHX is likely due to the emission wavelength (~ 310 nm according to the spectra in Fig. 5) being outside of our TEAS probe window (320–720 nm) in this case. However, given the proximity of the S_1 and S_2 states of *p*-MA in all three solvents, as just discussed, we cannot discard the possibility that this stimulated emission feature originates from the S_2 state, rather than the S_1 , which could be possible despite Kasha's rule and despite the low oscillator strength of the $S_2 \rightarrow S_0$ transition (see Table 1) due to the fact that stimulated emission is a phenomenon facilitated by laser conditions. Furthermore, in both ACN and CHX, a broad excited state absorption feature spanning 400–700 nm is also present, while in EtOH this feature is much less obvious (albeit still present). Given that, in EtOH, photoexcitation of *p*-MA is likely to populate mainly the S_1 state (see above), we suggest that the broad feature covering the red-edge of the probe window corresponds to excited state absorption from the S_2 state of *p*-MA (most obvious in CHX and ACN, where population of the S_2 state is more likely).

In all solvents, the evolution of EADS1 into EADS2 consists mainly of changes in signal intensity, with no large spectral shifts. This behaviour is indicative of mild geometry relaxation, likely taking place alongside solvent rearrangement. In particular, the stimulated emission features in the polar solvents become more intense within τ_1 , indicating excited state population migration towards an energy minimum from which fluorescence is more efficient. There is no evidence of IC between two states, nor

of any drastic geometry change during τ_1 (on either the S_1 or S_2 states); in EtOH, the evolution from EADS1 to EADS2 does evidence a slight red shift of the stimulated emission feature (see Fig. 4(f)), but this is likely associated with a geometry relaxation that leads to more significant vibrational cooling within τ_1 in this case. This combination of processes, *i.e.* vibrational cooling *via* mild geometry relaxation and solvent rearrangement, is therefore suggested to take place within $\tau_1 = 3.84 \pm 0.05$ ps in CHX, $\tau_1 = 1.35 \pm 0.02$ ps in ACN, and $\tau_1 = 12.8 \pm 0.1$ ps in EtOH.

It is worth noting here the significant differences in τ_1 across solvents, which do not follow the polarity trend. It is plausible that the different contributions from the S_2 state to this initial vibrational cooling step (which is minimal in EtOH) may introduce these differences and thus contribute to the lack of a trend along increasing solvent polarity. Nevertheless, and in particular for the case of *p*-MA in EtOH, for which τ_1 is significantly longer, the variations in the time over which vibrational cooling takes place are likely explained by different levels of solvent interactions. The temperature-dependent UV/Vis spectra of *p*-MA presented in the ESI† (see S1) reveal a blue shift in absorption with increasing temperature which is more pronounced in the polar solvents. This effect has been previously reported to be related to hydrogen bonding:⁴³ while polar solvents stabilize the excited state, the increasing temperature disturbs hydrogen bonds and the solvent stabilizing effect is increasingly lost. As a result, the energy of the excited state increases with increasing temperature and a blue shift is



With respect to the red edge of the probe window of these experiments, the observation in polar solvents is similar to that just described for CHX. The broad excited state absorption between 400–700 nm decays significantly as EADS2 evolves into EADS3, particularly for *p*-MA in ACN (see Fig. 7(e)). In addition, the stimulated emission feature seen in the data for both ACN and EtOH (not present in CHX), also disappears within τ_2 . We hypothesize that the stimulated emission feature present in the TAS for *p*-MA in ACN and EtOH originates from the S_2 state and that its decay, along with the decay of the broad 400–700 nm ESA, both correspond to an $S_2 \rightarrow S_1$ transition (as was the case in CHX), taking place within $\tau_2 = 526 \pm 6$ ps in ACN and within $\tau_2 = 135 \pm 1$ ps in EtOH (see Table 2). The significantly shorter τ_2 extracted for *p*-MA in EtOH, when compared to ACN and CHX, suggests a faster $S_2 \rightarrow S_1$ transition in this case. The S_2/S_1 internal conversion may be faster in EtOH due to the larger energy difference between the two states: this energy gap may result not only in less population of the S_2 state but could also lead to a more energetically favourable S_2/S_1 CI which enhances the driving force for motion from the S_2 state towards the S_2/S_1 CI. As was discussed for CHX, we take confidence in assuming τ_2 does not correspond to S_1 decay because our TCSPC experiments have revealed fluorescence lifetimes (for photoexcitation at 279 nm and monitoring the emission at 340 nm, see ESI†) of $\tau_{F1} = 1.029 \pm 0.002$ ns in ACN and $\tau_{F1} = 390 \pm 1$ ps in EtOH, which do not match the respective τ_2 values extracted from the TAS.

As a caveat, we note here that it is also possible that τ_2 in all solvents could entail ISC directly from S_2 and S_1 onto nearby triplet states, with the feature visible in EADS3 at ~ 390 nm corresponding already to a triplet state which then persists into the timescales of the LT-TAS; the second triplet excited state absorption feature between ~ 650 – 750 nm would then result from IC within the triplet manifold. However, this hypothesis is relatively less likely given that such an efficient rate of ISC would be at odds with the fluorescence lifetimes we measured

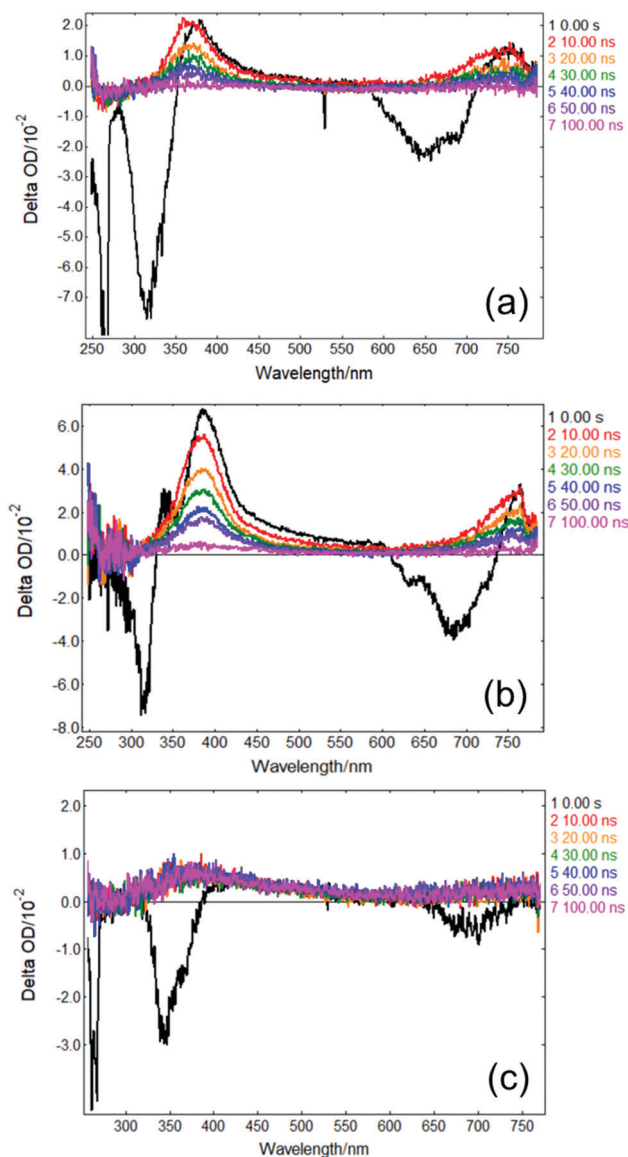


Fig. 8 LT-TAS spectra of *p*-MA in (a) CHX, (b) ACN and (c) EtOH, acquired with the ICCD detector at varying delays after the pump pulse (colour coding in the figure). Measurement conditions: $\lambda_{pu} = 266$ nm, spectrograph bandwidth = 0.7 nm, ICCD gate width = 10 ns, 25 averages/point. The fluorescence background was subtracted from each scan; however, this subtraction is not perfect at $\Delta t = 0$ ns due to the large signals from fluorescence and laser scatter, in combination with timing jitter of the laser pulse (the specification for Litron Nano S is < 0.5 ns). The negative signals at 532 nm and 640 nm in the $\Delta t = 0$ ns curve result from second-order diffraction of the scattered pump beam (266 nm) and sample fluorescence (320 nm) in the spectrograph.

for *p*-MA in all three solvents studied (see earlier discussion and ESI^\dagger), all of which are significantly longer than τ_2 .

The combination of all spectroscopic data collected for *p*-MA reveals an excited state behaviour for which the longest fluorescence lifetime is observed in a different solvent to the highest fluorescence quantum yield (CHX vs ACN, respectively). While the fluorescence lifetime of *p*-MA in different solvents follows a polarity trend (it increases with decreasing polarity, following

the order $\text{EtOH} < \text{ACN} < \text{CHX}$) the same cannot be said for the fluorescence quantum yield, which increases in the order $\text{CHX} < \text{EtOH} < \text{ACN}$. Moreover, if we assume the strength of the LT-TAS features to be correlated to the extent of triplet state population (rather than to a weak probe transition), it can also be said that the efficiency of ISC is different in the different solvents, being notably less efficient in EtOH (see Fig. 8). This behaviour points to a complex combination of relaxation pathways in *p*-MA which are affected in different ways by the solvent environment; particularly, it points to a scenario where alternative relaxation pathways compete with fluorescence, acting as efficient sinks for excited state population, but of which we have only indirect evidence. In summary, we find that excited state relaxation of *p*-MA in either CHX, ACN or EtOH proceeds *via* radiative pathways, with the relative contributions of each photophysical process being significantly affected by solvent polarity. We further suggest that the hydrogen bonding character of the solvent environment plays a particularly important role in the photodynamics of *p*-MA, potentially determining the activation/deactivation of its non-radiative decay pathways.

It is interesting to note that solvent environment has a critical effect on the photodynamics observed for both *m*-MA and *p*-MA, as summarized in Fig. 9. This is in stark contrast with *o*-MA, for which the photodynamics in both the gas-phase and in either polar or non-polar solvent were previously found to be virtually unaltered,¹⁴ most likely due to the stabilizing effect of the intramolecular hydrogen bond. The difference in

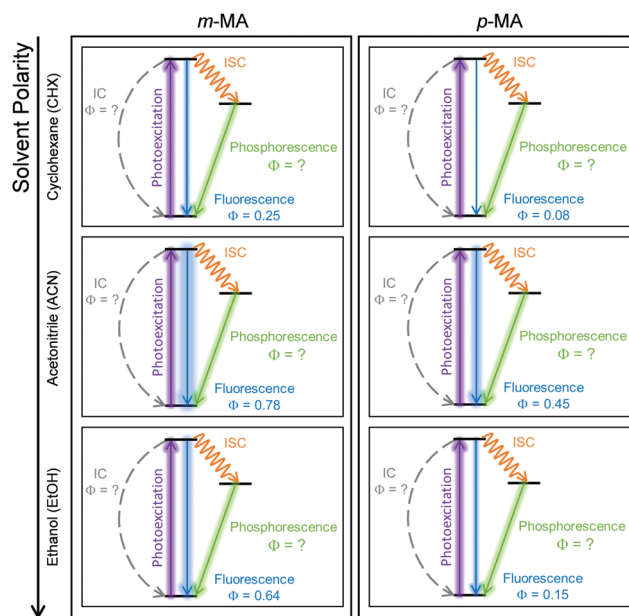


Fig. 9 Schematics summarizing the main findings of the present work. Both *m*-MA and *p*-MA undergo excited state relaxation *via* radiative pathways; the quantum yields of fluorescence are starkly affected by solvent environment but it is nevertheless always below unity. The quantum yield of phosphorescence was not determined, and the computational methods employed in this work could not straightforwardly locate any nearby CIs that would suggest IC taking place in these systems. This case study highlights the need for more advanced computational methods that take into account both implicit and explicit solvent interactions.



the extent of solvent effects on the photodynamics of these systems is particularly interesting given that the S_1 states of both *o*-MA and *m*-MA have some CT character (see ref. 14 and discussion above), but only the S_1 CT state of *m*-MA seems to be affected by solvent environment. In addition, while a CT character state was also previously suggested to account for the photodynamics of *p*-MA in the gas-phase,¹⁵ in this work we find no compelling evidence for the existence of such a state in solution. Substituent position is therefore found to significantly alter the photodynamics of these anthranilate derivatives, and also to impact their sensitivity to solvent environment.

In a sunscreen context, the work presented here reveals that photoexcitation of both *m*-MA and *p*-MA populates long-lived excited states upon photoexcitation, similar to what was observed in *o*-MA,¹⁴ and as such these are not ideal sunscreen candidates. However, while it can be said that radiative decay pathways play a significant role in the photodynamics of *o*-MA, *m*-MA, and *p*-MA, they each show a balance between radiative and non-radiative relaxation pathways upon which solvent environment has distinct effects. As such, a finer understanding of the photodynamics of *m*- and *p*-MA in solution is crucial not only for the understanding of their intramolecular dynamics, but importantly for a more detailed understanding of solute-solvent interactions more generally. Unfortunately, we find that gathering such detailed mechanistical insight for these systems is hindered by their complexity, which has revealed a challenge for the computational methods at our disposal. The work presented here may therefore serve as a case study of two molecules for which specific solvent interactions critically alter their photodynamics, supporting the case for the development of improved explicit solvent computational methods.

Conclusions

The present work explores the photodynamics of two amino-benzoate derivatives, *m*- and *p*-MA, in order to evaluate the effects of substituent position and solvent environment on their photodynamic behaviour. We find that *m*-MA behaves similarly to the previously studied methyl anthranilate, presenting evidence of excited state relaxation *via* radiative decay pathways. We find experimental evidence to suggest the S_1 state of *m*-MA has charge-transfer character that is sensitive to solvent environment, presumably leading to a deep S_1 energy minimum where excited state population can become trapped. The photodynamics of *p*-MA were found to be complex and also sensitive to solvent environment, in particular to the extent of hydrogen bonding, with fluorescence being significantly quenched in EtOH. We find, therefore, that despite the loss of the intramolecular hydrogen bond present in *o*-MA,¹⁴ the photodynamics of both *m*- and *p*-MA remain long-lived, and their excited state relaxations retain significant contributions from radiative decay pathways, a non-ideal behaviour for sunscreen UV filters.

Finally, we note that the computational methods at our disposal for this study have revealed insufficient to appropriately

model the experimental observations here reported for both *m*- and *p*-MA. The experimental data here reported may serve as a benchmark in future development of explicit solvent computational models.

Author contributions

N. d. N. R. was responsible for conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, validation, visualization, and writing (both original draft and review & editing). J. M. W. was responsible for formal analysis, investigation, validation and writing (review & editing). K. M. K. was responsible for formal analysis, investigation and writing (review & editing). M. A. T.-S. was responsible for formal analysis and investigation. M. A. P. T. was responsible for conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, and writing (review & editing). N. D. M. H. was responsible for funding acquisition, resources, software, supervision and writing (review & editing). V. G. S. was responsible for funding acquisition, project administration, resources, supervision and writing (review & editing).

Conflicts of interest

There are no conflicts to declare.

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